NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 230

DESCRIPTION AND LABORATORY TESTS OF A ROOTS TYPE AIRCRAFT ENGINE SUPERCHARGER

By MARSDEN WARE

REPRINT OF REPORT No. 230, ORIGINALLY PUBLISHED MARCH, 1926

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	sec	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/sec		horsepower	HP.
Speed		km/hr		mi./hr	M. P. H.
		m/sec		ft./sec	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight, $=mg$

g, Standard acceleration of gravity $=9.80665$ m/sec.^{2} $=32.1740$ ft./sec.^{2}

m, Mass, $=\frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} sec.^{2}) at 15° C and 760 mm $=0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m^3 $=0.07651$ lb./ft.^{3}

mk^2, Moment of inertia (indicate axis of the radius of gyration, k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord length.

b/c, Aspect ratio.

f, Distance from $c.\ g.$ to elevator hinge.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force. (Note that these coefficients are twice as large as the old coefficients L_C, D_C.)

i_w Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting with reference to to thrust line.

γ, Dihedral angle.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, 0° C: 255,000 and at 15° C., 230,000;

or for a model of 10 cm chord 40 m/sec, corresponding numbers are 299,000 and 270,000.

C_p, Center of pressure coefficient (ratio of distance of $C.\ P.$ from leading edge to chord length).

β, Angle of stabilizer setting with reference to lower wing, $=(i_t-i_w)$.

α, Angle of attack.

ϵ, Angle of downwash.

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Langley Memorial Aeronautical Laboratory

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SUMMARY

This report describes a Roots type aircraft engine supercharger and presents the results of some tests made with it at the Langley Field laboratories of the National Advisory Committee for Aeronautics. The supercharger used in these tests was constructed largely of aluminum, weighed 88 pounds and was arranged to be operated from the rear of a standard aircraft engine at a speed of 1½ engine crankshaft speed. The rotors of the supercharger were cycloidal in form and were 11 inches long and 9½ inches in diameter. The displacement of the supercharger was 0.51 cubic feet of air per revolution of the rotors.

The supercharger was tested in the laboratory, independently and in combination with a Liberty-12 aircraft engine, under simulated altitude pressure conditions in order to obtain information on its operation and performance. During an investigation of the influence on the operation of the engine of various types of air-duct connections between the supercharger and the engine, the supercharger was subjected to considerable rough treatment, which it endured very well, so that it seems apparent that the supercharger could well endure service handling. By the proper proportioning of the air-duct system, the engine would operate at all speeds as smoothly and free from vibration as the normal engine.

From these tests it seems evident that the Roots blower compares favorably with other compressor types used as aircraft engine superchargers and that it has several features that make it particularly attractive for such use.

INTRODUCTION

Since the density of the atmosphere decreases continuously with increase in altitude, the power developed by the normal aircraft engine decreases as its altitude of operation is increased to such an extent that the power developed at 20,000 feet is less than 50 per cent of that developed at seal level. Analyses have shown that this diminution in power can be prevented or at least reduced materially by supercharging, and applications of superchargers to service airplanes have resulted in marked increases in airplane performances. For any given service requirement, the results obtained by supercharging will be influenced by the type of the supercharger selected. Therefore, in order to permit intelligent selection to be made, the characteristics of the different types should be known.

Centrifugal air compressors operating at high rotative speeds have been employed as aircraft engine superchargers both in this country and abroad. Rotor speeds ranging from 6,000 to about 40,000 revolutions per minute have been employed in the various designs and multistaging has been used in some cases. The turbo-compressor supercharger developed by the Engineering Division of the Air Service is an excellent example of the application of this type of compressor for supercharging duty in this country. The positive-displacement types of compressors have not had such extensive trial. A reciprocating compressor and a rotating vane type have been tried but have mechanical limitations which militate against their utility for aircraft superchargers. The British made some trials with a supercharger patterned after the Roots blower, but the results have not been published. The Roots type has attractive

features and seems to have promise for use as an aircraft engine supercharger as indicated by tests that have been conducted upon the N. A. C. A. Roots type supercharger described in this report. Methods for driving these various types of compressorsh ave included direct-connected exhaust gas turbines, mechanical drives from the engine by belt and gears, and a gasoline engine having the compressor for its sole load.

DESCRIPTION OF THE N. A. C. A. ROOTS TYPE SUPERCHARGER

The National Advisory Committee for Aeronautics constructed a Roots type supercharger from designs made by the Clarke Thomson Research at the time the facilities of this research were placed under the direction of the National Advisory Committee for Aeronautics; G. W. Lewis, as engineer in charge of the Clarke Thomson Research, directed the making of the designs. The construction of the Roots supercharger is considerably different from that of the commercial Roots blowers, since for a supercharger having a given capacity it is necessary that the weight be a minimum compatible with the necessary strength. As a consequence, light alloy castings and alloy steels form the chief constructional materials for the supercharger. The speed of rotation of the rotors is increased considerably over that used in commercial practice in order to obtain greater capacity for a given displacement.

Consideration of the possible synchronization of the pulsating pressure of the air delivered by the supercharger with the pulsating pressure induced by the engine determined the relation of rotor speed to engine speed. With a 12-cylinder engine operating on the four-stroke cycle, there will be six inductions per revolution. With the Roots supercharger, there are two periods of delivery per revolution of each rotor, resulting in four pressure impulses per revolution of the two rotors. Therefore, in order that the frequencies of the pulsations produced by the supercharger and the engine may be equal, the supercharger rotor speed must be 1.5 times the engine speed.

If the intervals between inductions for the different cylinders of the engine were equal, this would give an opportunity to realize some benefit from the synchronization of the pressure impulses produced by the supercharger with the induction periods of the engine. While the pressure fluctuations produced by the supercharger presumably occur at equal intervals, the induction periods with the Liberty 12-cylinder engine do not, since the angle between the two banks of six cylinders is 45°. Furthermore, the character of pressure waves in the two cases may be quite different so that the maximum effects of synchronization probably can not be realized by this particular combination.

The N. A. C. A. Roots supercharger was designed originally to be mounted directly on the rear of a Liberty engine and to be supported solely by the engine. This mounting was not used, however, and in all of the tests, the supercharger was supported by the engine bearers extended, and was driven from the engine through a flexible coupling. With these changes, the liability of damage due to misalignment was reduced. An idea of the construction of the supercharger can be obtained from Figure 1.

The housing is made of aluminum castings, all of the castings being ribbed to provide strength and rigidity with minimum weight, as can be seen from Figure 1. A steel plate separates the rotor chamber from the gear compartment.

The supercharger rotors are shown in Figures 2 and 3. They are hollow castings, having a wall thickness of about three-sixteenths inch and are 11 inches long by 9⅝ inches in diameter. The contour of the rotors is cycloidal, except for a narrow portion of the tips, which is concentric with the axis of rotation, and a narrow flat portion near the hub; shallow clearance grooves are cut at the junctions of these surfaces with the cycloidal surfaces. The rotors are fitted with rectangular steel driving flanges which fit in machined recesses in the ends of the rotors and are fastened by machine screws. The driving flanges have internally splined hubs which fit on splines on the rotor shaft.

The rotor was constructed originally of an ordinary aluminum casting alloy. After approximately 100 hours of operation, they were replaced with rotors made of another aluminum alloy having a higher specific gravity and a greater tensile strength than that used at first.

Figure 4 shows the gears that drive the rotors. A gear operated at crankshaft speed meshes with a pinion forming an integral part of one rotor shaft, the ratio of these gears determining the rotor speed for a given engine speed. The rotor shafts are connected together by another pair of gears which serves to maintain proper relation between the rotors as well as to transmit torque from one rotor shaft to the other.

In the original design contact between the ends of the rotors and the housing was limited to a narrow ring near the shaft by a slight projection on the rotor ends formed on the flanged hubs. In most of the work all contact at the ends of the rotors was prevented by locating the rotors definitely in the housing by distance pieces inserted between the outer races of the rotor-shaft ball bearings and the bearing cover-plates.

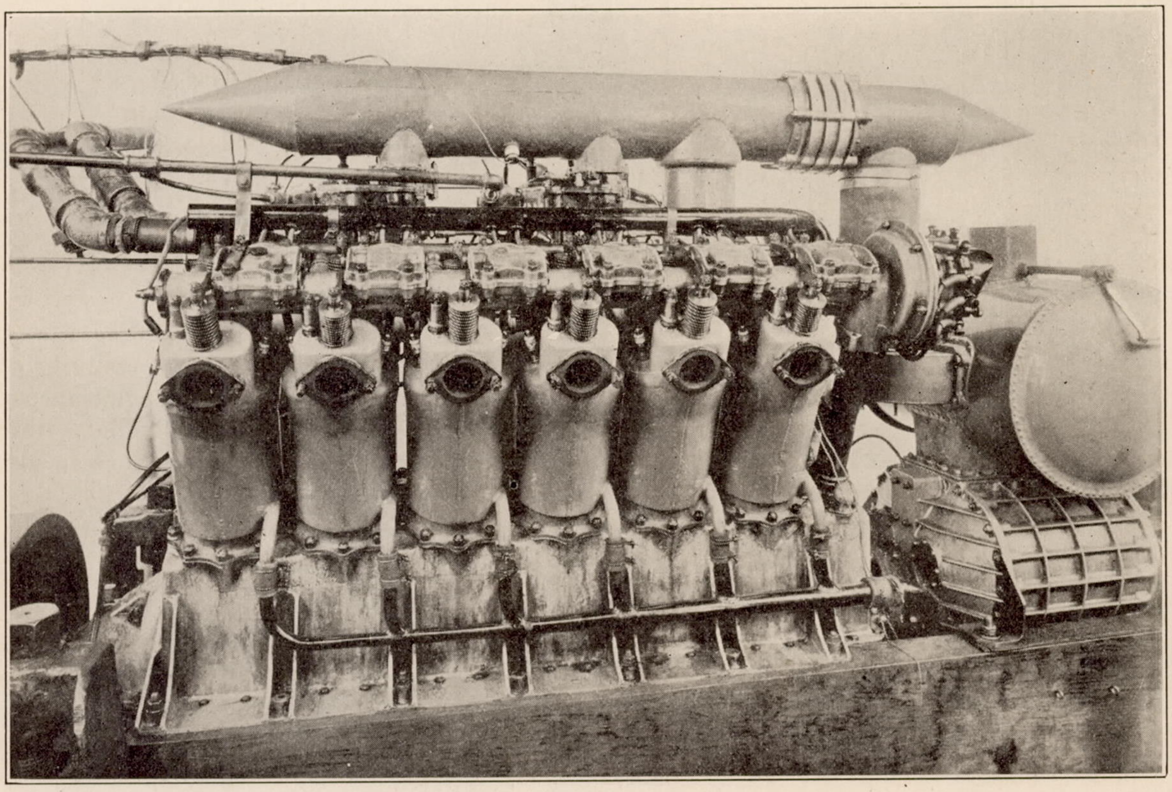

FIG. 1.—N. A. C. A. Roots type supercharger with Liberty-12 engine

It was originally intended that lubrication would be furnished from the main oil-pressure system of the engine. During the tests of the supercharger alone, however, it was found that a metering orifice, about No. 70 drill, had to be provided in the oil line to prevent overoiling. During the tests of the engine-supercharger unit the method of lubricating from the engine pressure system was discarded in favor of a hand lubricator connected to the supercharger gear case which gave greater assurance that proper lubrication of the supercharger would be maintained.

The air ducts provided with the original machine were made of cast aluminum, and were intended for use with standard Zenith carbureters. A single casting connected the two carbureters together at the bottom. From the rear carbureter a Y-shaped casting divided the duct system in order to pass around the Delco generator. Two arrangements were provided for connecting these ducts to the delivery side of the supercharger, one being an aluminum casting giving a direct connection with little volume and the other a sheet-steel tank of 1.8 cubic feet capacity. The design of the air connection was changed, however, to that shown in Figure 1, using inverted Stromberg carbureters with the original steel supercharger tank. The new parts were built chiefly of welded sheet steel.

A hand controlled butterfly valve, located in the short pipe shown in Figure 1 on the top of the supercharger tank, served to by-pass directly to the atmosphere all air not required by the engine and forms the sole supercharger control.

An automatic inlet valve, located in the air duct immediately in back of the rear carbureter, was introduced to permit the engine to draw air directly from the atmosphere in case the supercharger should fail. This was a poppet valve, 5 inches in diameter, which was normally held closed by its own weight and by the pressure in the air duct; the suction from the engine opening it if the supercharge air supply fails. In back of this valve there were four baffle plates made of 0.035-inch sheet steel, in each of which are drilled 30 holes, three-fourths inch in diameter. The holes in successive plates were staggered.

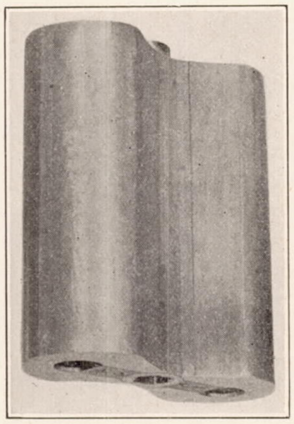

Fig. 2.—Aluminum rotor with steel driving flanges

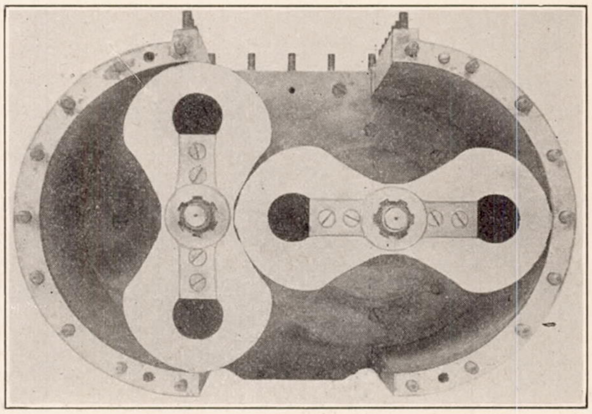

Fig. 3.—Supercharger with rear end plate removed

The supercharger complete with rotors made of the heavier aluminum alloy, coupling, and redesigned air ducts weighs 151 pounds. The main component weights are as follows:

	Pounds
Supercharger	88
Coupling	10
Supercharger tank	24
Air ducts	29

In making the alterations to the original design mentioned, minimum weight was not given much consideration so that the changes involved an increase in over-all weight of about 30 pounds.

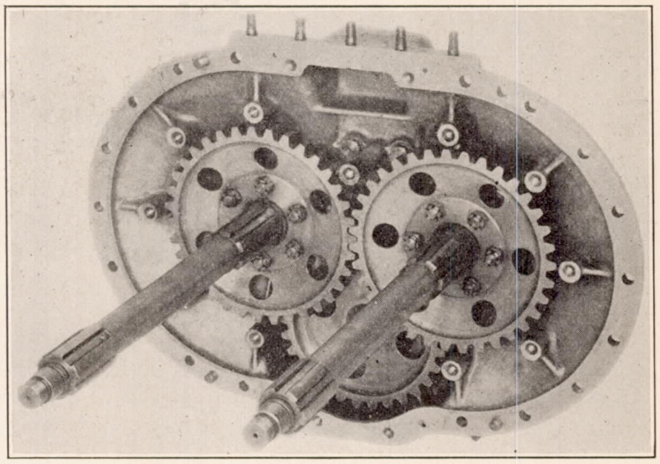

Fig. 4.—Gear case, gears, and rotor shafts

LABORATORY TESTS OF THE SUPERCHARGER

Tests of the supercharger as an independent unit were made with the supercharger connected to a 50–75 horsepower Sprague electric dynamometer. The inlet to the supercharger was throttled to simulate service pressure conditions. The air quantities were measured with thin-plate orifices patterned after those calibrated by R. J. Durley and reported in Volume 27 of Transactions of the American Society of Mechanical Engineers. Provision was made to use two orifices in parallel, so that sizes no larger than those calibrated by Durley would be required. Temperatures were observed by means of chemical mercury thermometers, and pressures by mercury, water and alcohol manometers. A special screw adjustment type alcohol

manometer was used to measure the drop across the metering orifices, which enabled the head to be read easily to within 0.005 inch. The scheme of the apparatus set up is shown in Figure 5, manometers and thermometers being indicated at the points of their introduction into the system.

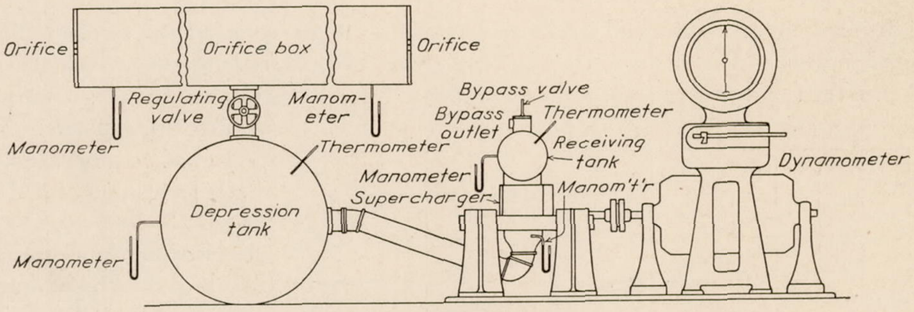

FIG. 5.—Arrangement of apparatus for laboratory test of supercharger

Measurements of power required and weight of air handled were made over a range of ratios of supercharger discharge to inlet pressures from 1.0 to 2.2 and for speeds up to 1,800 revolutions per minute. The various pressure ratios were obtained by varying the inlet pressure, the discharge pressure being held nearly constant. The actual runs were made at constant weights of air handled, the desired pressure ratios being obtained by varying the speed of rotation and the opening of the inlet gate valve.

The following methods were used in working up the plotted results for weight of air handled. The absolute pressure of the different parts of the system were obtained from the barometer and the different manometer observations. The following formula, given by Durley, was used in determining the weight of air handled:

$$W = C.630\ d^2 \sqrt{i/T}$$

where

W = weight of air in pounds per second.

C = coefficient of discharge for the orifice.

d = diameter of orifice in inches.

i = head over orifice in inches of water.

T = absolute temperature of air, Fahrenheit.

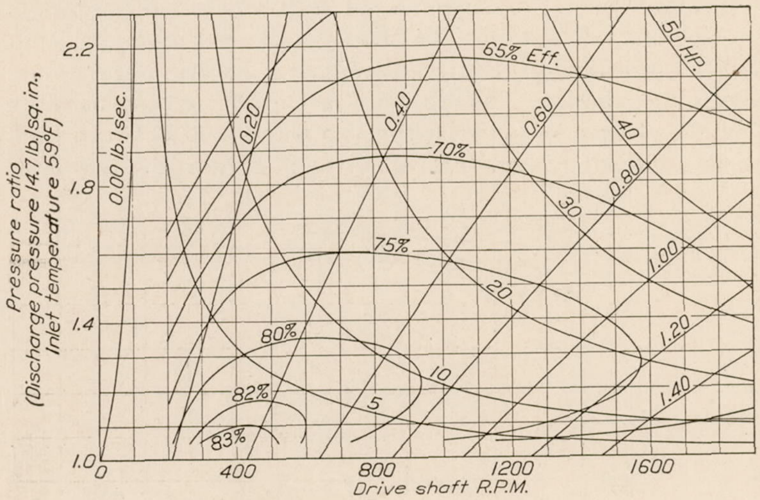

FIG. 6.—Power, efficiency, and air delivery

The coefficient used was that given by Durley, but modified as indicated by a series of experiments made to determine the effect on the orifice coefficient of causing the flow to take place in the reverse direction from that for which the orifice was originally calibrated. The effect of such reversal was insignificant for the purpose of these tests. The volume of air handled in unit time was determined from the density of the air at the supercharger inlet and the weight measured by the orifice meter. From this and the geometrical displacement, the volumetric efficiency of the blower was obtained.

Brake horsepower during the test was determined from the dynamometer torque scale and revolution counter readings. While the runs were so made that very nearly constant air weights were obtained, still there were small differences in air weights between the runs, so that the speed, power, and air volumes were reduced to the same mean weight basis by straight proportion. The amount of such reduction was at all times quite small. The horsepower theoretically

required to adiabatically compress and deliver 1 pound of air per second is given by the following formula:

$$\mathrm{HP.} = \frac{RT}{550}\,\frac{k}{k-1}\,\left(r^{\frac{k-1}{k}}-1\right) = .336\ T\ \left(r^{.289}-1\right)$$

This power divided by the observed brake horsepower was designated the overall efficiency.

Figure 6 is a plot of the results, the curves having been faired by successive cross-plotting. In Figure 7 constant speed curves of efficiency plotted against pressure ratio are shown for four interesting speeds. The power required to operate the blower with free inlet and discharge is about 3 horsepower at 1,800 revolutions per minute. Figure 8 gives the volumetric efficiency obtained.

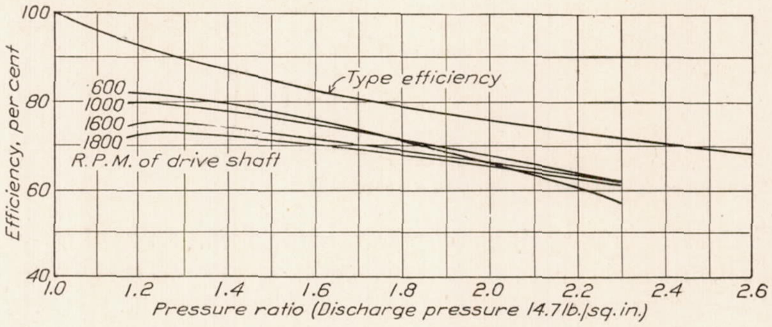

FIG. 7.—Theoretical and test efficiencies

Ratios of the absolute temperature of the discharge air to the absolute temperature of the inlet air, computed for various test conditions, are plotted on Figure 9, and a curve is drawn to represent the test results. This curve is closely approximated by another which is determined by the equation, $\frac{T_2}{T_1}=\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$ with "n" taken as 1.53. A curve showing the relations of these quantities for adiabatic compression, "n" taken as 1.4, is given also on this figure.

Slip speeds were obtained by blocking off entirely the inlet to the supercharger and, observing the speed required to maintain specified pressure ratios up to 2.2 with no discharge, the pressure on the discharge side being atmospheric. The slip speed will be affected considerably by the lubrication conditions and by the clearances between the two rotors and between each rotor and the housing. The slip speeds obtained in these tests are given in Figure 10. A greater amount of lubricant was used during these tests than was found desirable later in actual use of the machine. No tests were made to determine the effect of differences in lubrication and clearances upon these performance characteristics, but the effect may be appreciable.

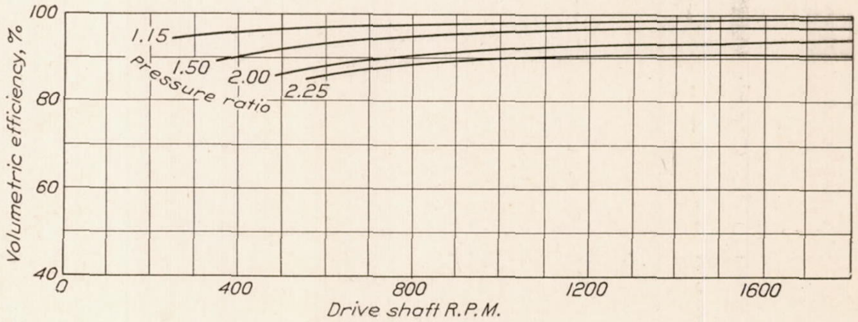

FIG. 8.—Volumetric efficiency

In order to obtain an indication of the mechanical limitations of the type, tests were made to determine the speed at which the rotor would burst when rotating by itself in free air. An aluminum alloy rotor failed at 9,600 R. P. M., while a magnesium alloy rotor made subsequently to these performance tests but similar in design to the aluminum rotor failed at 13,500 R. P. M. The speed of rotation of the supercharger rotors depends upon the speed of the engine and the gear ratio selected. The tests described in this report were made with a gear ratio of 1.5:1 so that with an engine speed of 1,700 R. P. M. the rotor speed is 2,550 R. P. M. During flight tests that were made later than the tests reported here, the gear ratio was increased to 1.95:1 giving a rotor speed of over 3,200 R. P. M. for an engine speed of 1,700 R. P. M. The machine was used considerably with this higher drive ratio and there was no evidence that such high rotor speeds imposed any important limitations.

It is interesting to note that commercial Roots blowers having the same displacement as the N. A. C. A. Roots supercharger, namely, one-half cubic foot per revolution of the rotor, have normal operating speeds of about 500 R. P. M. as against the supercharger speed of 3,200 R. P. M. with the higher gear ratio.

THEORETICAL EFFICIENCY OF ROOTS BLOWER

Figure 7 shows a curve marked "Type efficiency." This efficiency is the ratio of the area for the theoretical adiabatic card for a reciprocating compressor to the area of a rectangular card using the same pressures and inlet volumes. The rectangular card represents approximately the power required by a Roots blower.

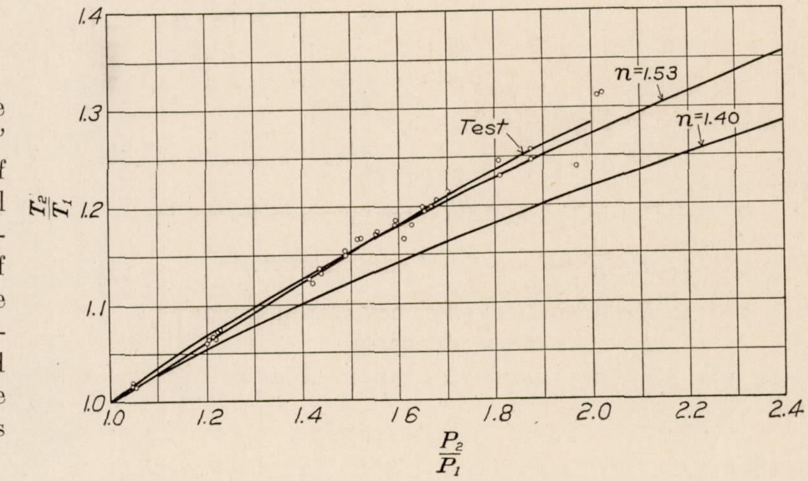

FIG. 9.—Temperature-pressure relations of air handled by supercharger

Referring to the diagrammatic outline of a Roots blower in Figure 11, it will be seen that the action of the impeller is to transfer a fixed volume of air "A" from the inlet side and at the inlet pressure to the delivery side, ignoring all losses due to leakage, and that this volume of air "A" is subjected to the full delivery pressure at "B" when a sufficient area has been opened at point "C" by the rotation of the impeller. At this moment

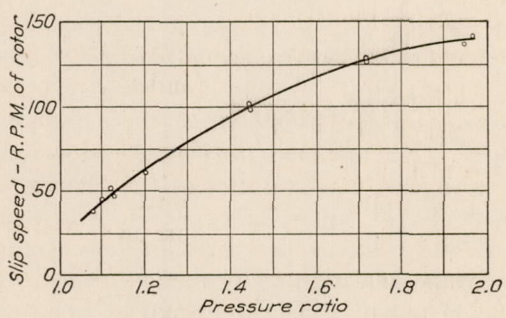

FIG. 10.—Slip speed

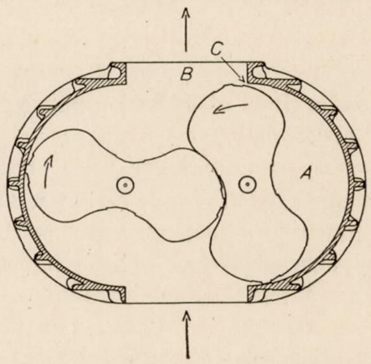

FIG. 11.—Diagrammatic cross section of Roots compresser

the air at "A" is suddenly compressed to the full delivery pressure, and the rotor then works against the delivery pressure during practically the whole movement required to displace the volume "A."

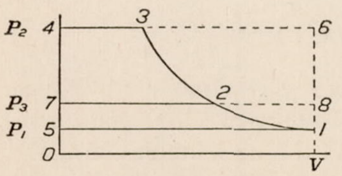

FIG. 12.—P-V relations of Roots and reciprocating compressers

The pressure-volume relation for this condition of operation is shown in Figure 12, where the area 1–2–3–4–5 represents the work required to compress adiabatically and deliver 1 pound of air from the pressure P_1 to the pressure P_2, a form of indicator card which is given approximately by piston compressors. The area 1–6–4–5 represents the work required to compress and deliver the same unit weight by the method of operation of the Roots blower The area between the line of instantaneous pressure rise along 1–6 and the adiabatic pressure rise along 1–2–3 represents the extra work done in the Roots type blower. It is apparent that this extra work is small as compared to the total work at low compression ratios but becomes a greater proportion of the total work as the compression ratio increases.

Numerical values of type efficiency can be obtained from simple mathematical treatment of the case. The work required to compress adiabatically and to deliver 1 pound of air, as shown by the area 1–2–3–4–5 in Figure 11 is

$$W_a = \frac{k}{k-1} P_1 V 144 \left(r^{\frac{k-1}{k}} - 1 \right)$$

The work of compression and delivery of 1 pound of air, according to the hydraulic card area 1–6–4–5 in Figure 11, is

$$W_h = V\ (P_2 - P_1)\ 144$$

where

P_1 and P_2 = initial and final pressures in lb./sq. in.

$r = \frac{P_2}{P_1}$ = the ratio of compression.

E = theoretical efficiency of Roots blower.

k = ratio of specific heats.

V = the volume of 1 pound of air at initial pressure and temperature conditions.

but

$$P_2 - P_1 = P_1\ (r-1)$$

so that

$$W_h = VP_1\ (r-1)\ 144$$

The theoretical type efficiency is evidently the ratio between these work areas, or:

$$E = \frac{W_a}{W_h} = \frac{k}{k-1} \left(r^{\frac{k-1}{k}} - 1 \right)$$

For air $K = 1.406$, so that

$$E = \frac{3.463\ (r^{.289} - 1)}{r-1}$$

Computed values of E for pressure ratios up to 3.0 determine the curve marked "Type efficiency" given in Figure 7.

Several methods have been considered for counteracting this characteristic reduction in compressing efficiency with increase of pressure ratio. For instance, the slow-speed commercial Roots blower has been provided with a Venturi restriction at the outlet of the blower for use with pressure differences somewhat above five pounds per square inch, which is intended to give higher efficiencies than would be obtained with the ordinary blower under these conditions. Brief trials were made with a Venturi discharge fixture and with well-rounded orifices, having orifice discharge coefficients for the two directions of flow of approximately 0.95 and 0.60, but no improvement was obtained. The installation of valves above the rotors would tend to reduce the back flow of air, so that the cycle would then approach more nearly that of the piston compressor. Several such valve mechanisms were studied briefly in the laboratory, but all of them imposed so great a pressure drop in passing the air through the valve that no benefit could be expected by their use.

LABORATORY TESTS OF ENGINE-SUPERCHARGER UNIT

After the tests of the supercharger as an independent machine were completed, it was connected to a 12-cylinder Liberty engine and subjected to further tests with a 300–400 horsepower Sprague electric dynamometer, in order to study the action of the unit under simulated altitude pressure conditions for the supercharger and to obtain some performance data under these conditions. The same arrangement of orifice box and depression tank was used as in the previous tests, but the delivery side of the supercharger was connected to the engine carbureters.

When using the original air-duct system and standard Zenith carbureters, very rough running was encountered over a wide range of speeds. Between 600 and 1,400 R. P. M., this

rough running was accompanied by violent back-firing in the carbureter and momentary cutting out of the entire engine. At 1,600 R. P. M., however, the operation was satisfactory. The rough operation noted was definitely attributed to the air-duct system.

A number of radically different systems of air ducts were tried, using Stromberg inverted and standard Zenith carbureters. These systems involved the use of various sizes and arrangements of receivers and pipes and various restrictions and baffles. With these different arrangements, improved operation took the form of narrowing the speed range over which the rough running was encountered. Satisfactory operation throughout the complete speed range was obtained by imposing considerable restriction in direct pipe connections, by using large receivers, or by giving careful attention to the proportions and forms of the various parts of the duct system.

The system adopted for flight test, shown in Figure 1, involved the use of the original receiver, having a volume of 1.8 cubic feet, at the discharge of the supercharger. When using the air-duct system over the carbureter, as shown in this figure, no attempt was made to reduce the size of the supercharger receiver. Recent tests made with another engine, however, have indicated that considerable reduction in size may be possible.

With the Stromberg inverted carbureters mixture adjustment is effected by means of an air leak from the atmosphere to the carbureter float chambers controlled by a valve located outside of the carbureter and connected to the float chambers by a tube. In the supercharger installation this tube can not be left open to the atmosphere, but must be connected to the supercharger air duct system in order to have the fuel flow through the carbureter jets. With the present installation this was accomplished by inserting a short tube and a control valve for mixture adjustment between each carbureter float chamber and the air duct over the carbureters.

The conditions of operation in these tests were different from flight conditions in several respects. Of these conditions two were radically different; first, in the laboratory tests the engine exhausted into air at approximately sea-level pressure for all supercharger inlet air pressures, and second, the temperature of the air entering the supercharger remained practically constant with changes in pressure instead of decreasing with pressure as in flight. The results were reduced to flight conditions by the use of rational reduction factors. The error introduced by the method of taking into account the differences in engine exhaust pressure has been shown to be relatively unimportant by tests that have been made since at the Bureau of Standards and reported in N. A. C. A. Technical Note No. 210. The method of taking into account the differences in temperature, however, has not been substantiated by test. Since the errors involved in the methods of making the reduction are quite uncertain the estimated power of the unit for flight conditions as obtained from these laboratory tests are not given.

The following extract from these data serves to illustrate the character of the test conditions:

Supercharger inlet pressure = 16.5 in. Hg. absolute.
Supercharger inlet temperature = 80° F.
Carbureter pressure = 29.8 in. Hg. absolute.
Carbureter temperature = 175° F.
Crankshaft speed = 1,600 R. P. M.
Brake power of unit = 326 HP.

By taking into account the differences between test and flight temperatures and pressures as referred to in the preceding paragraph, much greater power of the unit is obtained.

A brief study was made of the effects of varying the timing of the pressure pulsations produced by the supercharger with the pressure pulsations induced by the engine. With a large air-duct system that gave smooth operation of the engine no differences in engine operation or power were noted. With the smallest air-duct system used, rough operation was obtained with all adjustments and fair power comparisons could not be made. This study was not extended further, since it was evident that but little could be gained with this combination.

CONTROL METHODS

By supercharging aircraft engines it is intended to prevent or at least to reduce materially the diminution in power suffered by the normal aircraft engine as its altitude of operation is increased. It is necessary, therefore, that the rate of air delivery to the engine when supercharging at considerable altitude above the ground, be roughly the same as the consumption of the normal engine when operating at ground level. At a fixed speed, the Roots supercharger delivers air at a constantly decreasing rate as the altitude of operation is increased, since for this type of machine, the rate of air delivery with 100 per cent volumetric efficiency varies directly with the density of the air at the inlet to the machine and its speed of rotation. Some control means must be provided, therefore, in order to obtain the desired end.

The necessary control may be secured in several ways; first, by operating the supercharger at a fixed engine-supercharger speed ratio, with the inlet side of the supercharger open to take air at the density of the operating altitude and returning to the atmosphere all air in excess of that required by the engine; second, by operating the supercharger at a fixed engine-supercharger speed ratio but with the inlet of the supercharger throttled at low altitudes, so that the density of the air handled by the supercharger will be practically constant; third, by continuously changing the engine-supercharger speed ratio, so that the supercharger will deliver air at just the rate required by the engine. The power required to operate the supercharger by each of the control methods for a constant engine speed, as estimated for flight conditions and using the laboratory tests as a basis, is shown by Figure 13. The three curves intersect at the point where the speed of the supercharger with the method involving speed change is the same as in the other methods, and the by-pass valve is fully closed and the inlet valve is opened fully for the methods involving these types of controls. The weight of the fixtures for the first and second methods would be about the same, but the method requiring speed change would probably involve a much greater weight because of the mechanism required. The second method involves no more complication than the first, but does take considerably more power at lower altitudes and always delivers air having an absolute temperature at a nearly constant ratio to the absolute temperature of the inlet air, due to the fact that the supercharger itself is operating with nearly the same pressure ratio all the time. With this method, then, the supercharger discharge air temperatures will be excessive near the ground and some method of cooling the air delivered to the engine probably would be necessary.

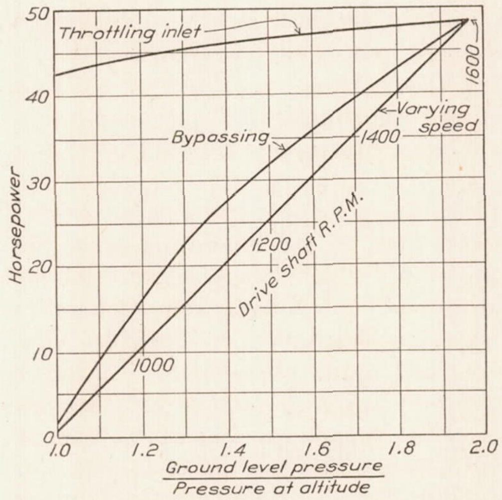

FIG. 13.—Effect of method of control on power required

The first method of control was used in the tests of this supercharger. With this method the temperature rise through the supercharger is a minimum. The power required approaches very close to the minimum as obtained by the variable speed ratio method and does not entail the complication of control, and probably results in quicker response to the control than the latter method. The weight of the fixtures for the first method also is favorable to its selection.

POSSIBILITIES OF THE ROOTS TYPE SUPERCHARGER

These tests indicate that the Roots blower as a type has several features that make its use as an aircraft engine supercharger attractive, although they can not show either the extent or the degree of its value. The machine used in these tests was the first to be built from this design and endured over 100 hours of operation without requiring the replacement of any important parts. Since during a large part of the time the supercharger was subjected to abnormally rough treatment and since the design embodies many features that are a radical departure from commercial practice for this type of machine, this performance indicates that the type is well

adapted for aircraft engine supercharging from a durability viewpoint. While the reciprocating compressor is attractive when the power for the actual compression and delivery of the air alone is considered, mechanical friction losses, together with mechanical limitations, make it unsuitable for very broad application to aircraft engine supercharging. For many applications in this field the Roots type supercharger has power requirement characteristics that are the equal if not the superior of other common types.

While speeds of rotor operation much in excess of those employed in commercial service were involved in these tests, the tests have shown that this condition is no handicap to the use of this machine and indicate, moreover, that still higher speeds could be used as far as structural characteristics are concerned. The use of higher speeds for a given capacity would permit a direct reduction in the weight of the supercharger and by virtue of the increase in the frequency and the reduction of the amplitude of the pressure pulsations, would permit smaller air ducts with further economies in weight of the complete unit. Actual experience is necessary to determine what could be realized in this respect. While it may be thought that inertia stresses may impose the most serious limitation, there have been no indications from work done on this machine that this condition has been even approached. While the pressure pulsation conditions were stated to be improved with increase in speed of operation, experiences encountered in these tests show that the pulsation conditions existing in the present tests could be readily handled so that engine operation would not be affected adversely.

The centrifugal compressor has received far more attention to date than any other type for use as an aircraft engine supercharger. This type of compressor has had considerable use as an exhaust gas driven supercharger. In this case both turbine and compressor are essentially very high speed machines, and their combination forms an admirable unit for certain purposes. The position of the centrifugal compressor is not as favorable, however, when it is used as a mechanically driven machine.

If a centrifugal compressor is driven at a speed bearing a fixed ratio to the engine speed, the ratio of absolute temperatures at the inlet and discharge of the supercharger will not change much with change in altitude at all altitudes up to that at which the supercharger capacity is just sufficient to maintain ground-level pressure at the carbureters. Then, the carbureter temperature at ground level will exceed considerably the atmospheric temperature which is already sufficiently high under most conditions. If the equipment were designed to maintain ground-level pressure at any but very moderate altitudes, the carbureter temperature at the ground level would surely be prohibitive unless elaborate cooling means are provided. In contrast to this condition the Roots type as utilized in these tests compresses the air almost imperceptibly at the ground, and the carbureter temperature is but little in excess of the ambient atmospheric temperature.

Because of the characteristics of the centrifugal compressor, the power required to drive it at ground level at a speed having a fixed relation to the engine speed will differ but little from the power required at the altitude at which the supercharger has just sufficient capacity to maintain ground-level pressure. In contrast to this condition the Roots type, even though it handles a large quantity of air, requires comparatively very little power at ground level since the amount of compression of the air is practically imperceptible.

The exhaust gas turbine driven supercharger will not respond instantaneously to the supercharger control, while, on the other hand, any mechanically driven supercharger can be arranged readily to give instantaneous response to the control. The Roots type, in addition, has more favorable power and air temperature conditions than any other compressor that has yet been seriously considered. Maintenance of mechanical clearances which would seem to be a handicap of the Roots type have not proved troublesome in these or later tests.

CONCLUSIONS

The tests reported herein serve to indicate that the Roots type blower is well adapted for use as an aircraft engine supercharger. From considerations of durability, low power requirements, control, and heating of the air handled, it appears especially well suited for many service requirements.

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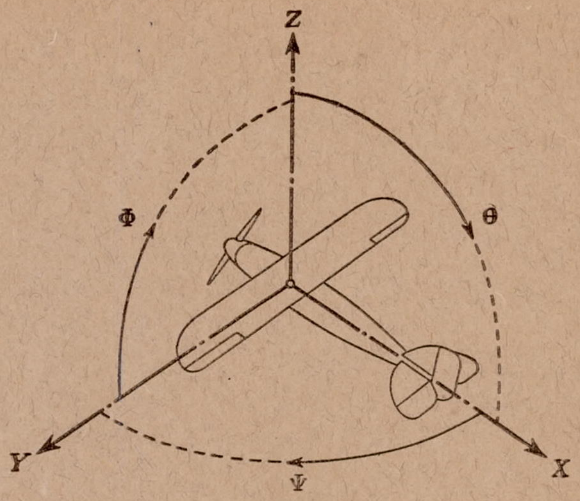

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	Φ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	Θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	Ψ	w	r

Absolute coefficients of moment

$$C_L=\frac{L}{qbS}\quad C_M=\frac{M}{qcS}\quad C_N=\frac{N}{qfS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.
p_e, Effective pitch
p_g, Mean geometric pitch.
p_s, Standard pitch.
p_v, Zero thrust.
p_a, Zero torque.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slip stream velocity.

T, Thrust.
Q, Torque.
P, Power.

(If "coefficients" are introduced all units used must be consistent.)

η, Efficiency $= T\ V/P$.
n, Revolutions per sec., r. p. s.
N, Revolutions per minute., R. P. M.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 HP = 76.04 kg/m/sec. = 550 lb./ft./sec.
1 kg/m/sec. = 0.01315 HP.
1 mi./hr. = 0.44704 m/sec.
1 m/sec. = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.